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Real-Time Tools for Situational Awareness and Emergency Management in Transport Infrastructures

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Abstract: Critical transport infrastructures such as interchanges, long tunnels and bridges represent the most vulnerable environments within a transportation network; they are characterized by limited access/egress points and high volumes of users in close confines. A number of factors must be addressed to ensure maximum safety of both travellers and emergency service personnel; these include emergency preparedness, timely support for the decision-making process, and planning of optimal interventions in emergency management situations. This paper discusses the integration of wireless sensor networks (WSNs) and virtual reality (VR) to support the self-evacuation of travellers and operational procedures of rescue personnel within these environments, focusing on two key aspects of emergency operations: (i) collecting real-time data and (ii) improving the timeliness of first responders through efficient provision of the collected data. Testimonials, technical results and recommendations collated from two pilot installations realised within the EU-funded SAVE ME project demonstrate the qualitative and quantitative impact of such an approach on emergency situation management.

Keywords: wireless sensor networks, indoor localization, virtual reality, roadside applications, evacuation process simulation

Biographical notes: Ing. Laura Coconea holds a Master's degree in Computer Science Engineering and since 2009 has been collaborating with SWARCO Mizar and Politecnico di Torino on research projects regarding wireless communication technologies applied to Intelligent Transportation Systems. She has been coordinating installation & test activities for WSN systems provided by SWARCO Mizar in EU-funded projects COSMO and SAVE ME. She is now working on I2V communications and is involved in standardization activities for I2V Applications.

Dr. Uberto Delprato holds a Master's degree in Nuclear Engineering and has a 20 years' experience in environmental monitoring and in developing ICT applications for environment and security. He is founder and CEO of IES Solutions and has been coordinating the EU-funded projects ODIN, LOCCATEC, REACT, REACH112. He is currently coordinating the FP7 Support Action ESENET (Emergency Services Europe NETwork) and the CIPS project REFIRE (REFerence Implementation of interoperable indoor location and communication systems for first REsponders). He is member of the Advisory Board and of Vice-Chair of the Operations Committee of EENA (European Emergency Number Association) and advisor to the FEU (Federation of the European Union Fire Officer Associations). He is also founder member of the Public Safety Communication Europe Forum.

Mr. David Prior is a commercial technology innovator with extensive experience across a wide range of technical disciplines and operational domains. Previously head of Research and Development for a large defence contractor, David has spent the last five years working to develop technical strategies for a number of start-up companies: including Simudyne in relation to the EU SAVE ME project. Now focused on developing Xuvasi as a key player in the innovation sector, David's work encompasses simulation systems, big data, visual analytics, hyperlocality, open-source intelligence, healthcare data management, and crowdsourcing platforms and services.

Prof. Guido Albertengo received the Electronic Engineering Degree from Politecnico di Torino in December 1980, "summa cum laude". Since 1991, he has been an associate professor with the Department of Electronics and Telecommunications of Politecnico di Torino working on network architectures for providing advanced services, such as QoS-based routing, message relaying and mobility support. More recently, he has focused on Wireless Sensor Networks, designing some custom protocols (such as the one designed for SWARCO Mizar prototype provided in SAVE ME) for energy-efficient, guaranteed bandwidth WSN, and is now also working on I2V communications.

Prof. Phil Blythe CEng, FIET is Professor of Intelligent Transport Systems (ITS) and Director of the Transport Operations Research Group at Newcastle University. Phil's research portfolio covers a wide range of areas where ITS has been applied to transport including: wireless communications; road user charging; smart payment; assistive mobility and technologies to support older drivers, future intelligent infrastructure/smart cities and electro-mobility. His primary research is forward looking and attempts to bridge the technology-policy gap in terms of what technologies may evolve to meet

future policy objectives or indeed influence future policy thinking, particularly in the smart city/smart transport domain and to meet the three main challenges currently facing transport, namely: congestion, climate change and future energy vectors. Internationally, Phil coordinates four European projects with over a 100 partners from 23 countries and was the coordinator of the SAVE ME project. Phil has acted as an advisor to the UK and European governments in various areas of intelligent transport and more recently also in the electromobility and smart cities agendas.

Dr. Gareth Evans is a Newcastle graduate, holding a BSc (Hons.) in Surveying and Mapping Sciences followed by an MSc in Transport Engineering and Operations (from TORG). He then moved to the University of Glasgow to read for a PhD in Public Transport Cartography, before returning to TORG between 2008-2014 to join the research staff where he has worked on a range of projects. Gareth often played a key role in survey and evaluation tasks within research projects, and successfully co-ordinated the EU-funded SAVE ME project from 2009-2012. He has since left Newcastle University to take up a strategic transport co-ordination post at Intu Metrocentre, Europe's largest shopping and leisure complex, where he applies his expertise from the academic environment in a commercial context.

Mr. Dan Brennan holds a BSc in Electrical Engineering and prior to joining TORG, he was a Research Assistant with the School of Electrical and Electronic Engineering working on high temperature resistant Wireless Sensor Networks. Dan plays a key technical role in TORG's research activities, developing new technologies and integrating a range of sensors to produce novel systems for various research projects including the user-localisation for the SAVE ME project and instrumenting on of TORG's Electric Vehicles with a suite of detection sensors and assistive HMIs.

1 Introduction

The correct determination of strategies and subsequent implementation of real-time communication and visualization systems can save a considerable amount of precious time during a rescue operation in confined spaces. When a crisis management intervention is needed, the potential to inappropriately manage, or unintentionally create an even worse situation, through human error and/or inadequate awareness of the whole situation, is particularly high. Confident co-ordination of actions, combined with efficient communication within, between and across teams, coupled with a high level of decision making under extreme levels of stress, are needed to deliver an effective emergency management response by large scale and complex organizations. To achieve this, both operations and training must address technical and non-technical aspects.

This article is a revised and expanded version of a paper entitled “Exploitation of wireless sensor data in virtual reality for the provision of comprehensive support to tunnel safety training and emergency management” presented at Road Safety and Simulation International Conference, Rome 2013 (Coconea L, 2013) and illustrates how co-operation between WSN and VR technologies, tested under realistic conditions in the EU FP7 SAVE ME project, can support emergency operations by improving the work of rescuers and thus help to save members of the general public. SAVE ME focused on the development of a system to both detect incidents in public transport terminals and other critical infrastructures (e.g. tunnels and other confined facilities) and support the timely provision of optimal evacuation guidance. Using application areas including metro (subway) terminals and road tunnels, SAVE ME focused on leveraging WSN capabilities to provide critical data that could then be used to provide optimal mass evacuation guidance to the general public and, giving special emphasis to vulnerable travellers, personalised guidance where required (SAVE ME, 2009).

A critical task in the project was the selection of optimal sensors and communications technologies capable of detecting a disaster event, providing environmental monitoring and localization of users (both travellers and rescuers) during the evacuation process. Having a further requirement to provide near real-time information, dedicated WSN prototypes were designed and implemented for both application areas. As all individual components of the SAVE ME system were envisaged to eventually operate as an integrated system, a custom communications schema was developed to allow end-to-end information sharing from WSN to simulation and VR, and all points in between.

This paper discusses the architecture of a generic rescuer support system based on the WSN and VR components integrated through the techniques developed in the SAVE ME project, before presenting the SAVE ME trials and results achieved and finishing with the conclusions.

2 Related work

Existing studies on emergency management show how proper situational awareness and care for the protection of critical infrastructures, may help to decrease the consequences and speed up the recovery process (Luiijf E., 2011). Therefore complete, accurate, and real-time situational awareness is essential for emergency responders and others who are responsible for controlling the dynamic evacuation process. Inadequate situational awareness is cited as one of the primary factors in accidents attributed to human error (Reichenbach S., 2009).

The potential use of WSNs in emergency management has been present in the literature since 2000. Nevertheless, a survey (Silva A., 2013) analysed over 20 WSN-based systems addressing various aspects of disaster management (pre/post disaster, monitoring/event detection, situational awareness, localization, simulations, experiments) and concluded that such technology is still not widely considered at the emergency preparedness documentation of governmental or telecommunication organizations around the world. This is mainly due to the drawback represented by the economic feasibility while respecting the technical requirements related to functionality and reliability.

Further work related to the same topic highlights the fact that WSNs for disaster monitoring are still emerging technologies and much of the literature available is still theoretical: practical deployment guides using actual experience from field trials are few, if any (Ramesh M.,2011). Furthermore, the paper specifies a set of processes for the design of such systems and among the requirements also addressed is data visualization, as the requisite architecture has to be developed with the goal of effective and fast streaming of data.

Previous work in relation to the use of 3D virtual world /VR environments for the provision of situational awareness and training services saw culmination in the work of the US Army Research Laboratory in relation to their Military Open Simulator Enterprise Strategy (MOSES). MOSES built on previous work in this domain in relation to the provision of immersive environments for the training of first responders and similar roles in relation to major incidents (in solutions such as ADMS, from ETC Simulation of Florida, USA). MOSES was, however, distinct from previous approaches in that it looks to leverage an open-source code base rather than a dedicated – and expensive - commercial games engine. Between MOSES and the solution presented here lies the work of Daden Ltd (based in Birmingham, UK) providing immersive, standardised training to police and other first responders.

It should be noted that the state of the art in the application of VR systems to the situational awareness and training domains had been primarily led by the commercial sector. Where such technologies have been employed in academia and research environments previously, their use has been restricted to the provision of immersive vehicle simulators (for example, for driving and flight training) rather than the more practical applications required by the SAVE ME project. The innovation within the SAVE ME project not only derives from the focused use of VR technology for both training and real-time operational capabilities, but also from the extension of VR technology to directly reflect the real world context. Aspects reflected from the real world – in near (subject to network latency) real time - include the current accessibility for the facility at hand; the near real time positions (again, subject to network latency) of people within that facility, and the location and severity of incidents occurring within that facility.

There are also other challenging initiatives in this research field to be found in the literature: the CAPEVACUATION project presented an emergency evacuation system for corridor traffic control, which integrates both optimization and macroscopic/microscopic simulation methods (Liu Y., 2006); CROWD-MAGS dealt with research development in simulation, optimal routing and guidance (Moulin B, 2010); the RUNES project aimed to provide the middleware for networked embedded systems and its application in a disaster management scenario (Toth A., 2008).

An overview of existing tools and systems for emergency management found that although the literature provides numerous examples of applications to crisis response, such as such as Turoff‟s DERMIS, The American NIMS, Google’s Person Finder Tool (Dorasamy M., 2011) there is a clear research gap in the area of knowledge management systems for disasters.

3 Proposed approach and technologies

The proposed approach, derived from the SAVE ME experience, is an unique combination of systems/models for assessing human behaviour in emergencies, emergency detection and communication systems along with a decision support system for supporting operators and emergency personnel, all of which are underpinned by guidelines and training schemes for all users.

The methodology makes use of WSN technology for situational awareness. The first WSN-based system is uniquely able to provide multiple functionalities: pre/post disaster environmental monitoring and event detection, mobile node localisation and LED-based signalling. It represents the evolution of an already existing (pre-commercial) system based on low dimension, low cost, low power and low maintenance but isolated nodes (integrating GPRS communication capabilities) into a distributed version connecting

nodes in a wireless network. Therefore, it overcomes the major drawback of solutions already existing in the literature, related to practical application and economic feasibility. A second WSN-based system aims to extend the localisation capabilities in terms of scalability and topology.
A novel VR-based solution to the provision of contextual situational awareness in emergency responses and improved realism in training activities completes the chain.

3.1 WSN-based system for road-side applications

Recent research targets WSNs as a breakthrough technology for road traffic management and road safety applications, however a fully integrated solution is currently not available (Pascale A., 2012). Traffic measures and events are now typically collected using inductive loops and cameras, whilst new types of roadside sensors are undergoing field operational tests, such as those presented within this paper. Not only can these sensors identify traffic intensity, but they can also detect congestion and even register incidents occurring on a road. This is achieved by using a large number of nodes deployed along the roadside, with inter-node distances ranging from 50-100m, forming a linear topology sensor network. To minimize the cost of such systems, nodes are solar or battery powered, and a radio system is used for communication: the resulting network is therefore a Linear Topology WSN, or LT-WSN.
Low energy consumption, as well as the low latency required by this type of WSN, meant all currently available protocols for WSN were unusable. Thus, a new protocol in the ISM 2.4 GHz band with low latency and low energy consumption had to be designed and implemented. LT-WSNs have already been investigated (LEACH, PEGASIS, APTEEN projects) and some results are already available in the literature but in general the focus thus far is on maximising energy efficiency (Zhang S., 2011, Zimmerling M., 2008), whilst neglecting crucial aspects for this specific application field, such as low latency, network reliability, high density of the sensors and synchronization (Zimmerling M., 2007). Moreover, the resulting number of sensors in a single network should be in the order of the hundreds (e.g. 5 km of road can be covered by 100 sensors at spacing distance of 50m).

3.1.1 System Design

The WSN system presented in this paper proposes an innovative road traffic safety solution comprising a set of intelligent, autonomously powered nodes installed by the roadside, connected through an auto-configuring, adaptive and low-power wireless network employing gateway uplinks for the forwarding of data to a control centre. The WSN prototype described herein was completed through a formal design and development process within the SAVE ME project providing a packaged unit for traffic monitoring, environmental sensing, event detection, indoor localisation and signalling functions for support to emergency response in road tunnels.
The WSN node comprised two parts: the node head (Figure 1), integrating the sensors for all required features with a wireless communications module, and an attached power supply containing batteries. These WSN nodes can be placed along the roadside on any available support (e.g. steel barrier, Jersey rail, tunnel wall).

Figure 1 WSN node: the head

Different types of sensors mounted on the node head can be used to acquire measurements associated with passing vehicles (pyro-electric sensors), vibration on roadside steel barriers (accelerometers) or environmental conditions (temperature, humidity and luminosity sensors) and other data points of interest (e.g. CO detectors). A number of General Purpose Input-Output (GPIO) connectors in the WSN node design are used for the incorporation of LED-signalling services across the WSN footprint. These signalling capabilities aim to provide post-disaster dynamic collective guidance, by creating a green light path towards the closest exit or safe point and a red-flashing light indicating the danger area(s). Moreover, unlike classic static signage, dynamic forms of guidance are able to adapt during the evacuation process and being autonomous in terms of power supply do not depend on the surrounding infrastructure and mains supply.

3.1.2.Networking

As a network for roadside applications is composed of a high number of low-power, wireless connected nodes arranged in a single line and placed by the roadside (i.e. a LT-WSN), the use of standard WSN protocols, such as ZigBee (Wang Z., 2011) was not applicable, primarily due to device limitations related to the number of child routers and to the addressing system (Texas Instruments, 2008). Therefore, it was mandatory to study a new protocol which was able to take advantage of the linear topology to minimize the energy needed for correctly delivering data collected by the nodes. Another challenge was to enable the correct transmission of data packets in a network where it could be necessary to pass through up to 100 relay nodes in order to reach a gateway. This latter requirement derived from the need to cover stretches of roads up to 5 km with a single network.

To address these constraints, a novel and innovative dedicated Media Access Control (MAC) protocol was designed. It takes advantage of the linear structure of the network to provide the desired quality of service to the application domain. In this protocol, each node can, under normal operating conditions, reach four other nodes (two on either side) with its radio signal. This makes it possible to implement a multi-hop delivery protocol with two-hop steps, thus reducing the delivery time at the expense of the energy required, or to implement a single hop delivery protocol, minimizing the energy required. The chosen approach was to use the higher energy required by a two-hop step to reduce the packet loss probability.
Moreover, the linear topology allows the available time to be divided into two periods: the first, which implements the logical downlink channel, allows information to travel from Gateway to nodes up to the Terminator (i.e. the last node in the chain); the second, which implements the logical uplink channel, enables information to travel from the Terminator to the Gateway. The resulting logical topology is the Active Folded Bus (AFB), previously used extensively for experimental networks with both active and passive nodes, and the Medium Access Control (MAC) protocol becomes a Time Division Multiple Access (TDMA) protocol. Nodes are synchronized by a master timing node, which is the gateway itself. Figure 2 shows the network topology and the logical channels.

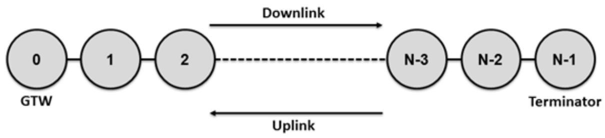

Figure 2 Network topology and logical channels

The MAC protocol is fairly simple: the Gateway periodically sends a Beacon packet onto the logical downlink channel, followed by the packets containing Commands to be sent to nodes. Each node uses the Beacon to stay synchronized with the Gateway, executes the command(s) received and forwards Beacon and Commands bound for downstream nodes. When Beacon and Commands reach the Terminator the Downlink period ends, and the Uplink period begins: the Terminator sends Response packets towards its neighbouring downstream nodes on the logical Uplink channel; intermediate nodes append their Responses to the incoming packet and forward all Responses. The cycle ends when the Responses arrive to the Gateway.
The messages are the data units of the AC sublevel protocol. There are present following types of messages:

- BEACON: is generated by the gateway and propagates along the downlink: is used in order to synchronize the nodes from the chain and to transport the commands toward the nodes
- EMERGENCY_BEACON : used instead of the beacon when the chain is interrupted
- CAR: generated by the terminator and propagates along the uplink: is used in order to collect data from the nodes and transport it towards the gateway
- P2P: used during the connection between a node in the chain and an external node in order to establish a point-to-point connection between them for data transportation

The format of the message is presented in Table 1.

MSG_TYPE	MSG_NUM	MSG_CHECK	MSG_CNTRL	MSG_DATA
2b	10b	4b	MSG_CTRL_LEN	MSG_DATA_LEN
2B				
				0 ÷ 4096B

Table 1 Message format

Within the field MSG_DATA are situated Informative Units (IU):

- commands: when they are used in order to send nodes commands for chain control
- confirmations: when they are used in order to transport collected data from nodes to gateway
- data: when they are used to confirm receiving a command without any other associated data

The access control defines the timing mode, the timings that nodes use in order to access the channel and the transmission procedure of data to the GTW and the scope of access control is to:

- Realize the logic topology
- Permit the propagation of an unique BEACON for every cycle
- Permit the propagation of multiple CAR for every cycle
- Permit the transmission to the GTW the data generated by the nodes

In order to reach the first three goals, a decision was adopted that, without losing the obtainable performance, permits the simplification of the operations that the nodes need to perform. All channel access operations take place periodically: the BEACON, that propagates downlink, needs to occupy a constant number of BEACON slots, as the single CAR has to occupy CAR slots along the uplink. A slot is needed in order to transmit a segment, so the slot number equals the segment number. In order to reach the last requirement, the joining of two different data send techniques was chosen: the first a non-deterministic one, suitable for asynchronous UI transmissions, the other deterministic one, suitable for the transmission of periodical IU and large data quantities.
The MAC protocol also takes into account the loss of packets, which can severely affect the correct delivery of a packet when the number of hops is high: the capability to send the same packet to a pair of downstream nodes makes it possible to correctly deliver the packet even if only one out of the two copies is correctly received. Mathematical analysis has been performed on the transmission technique, calculating the delivery success probability as a

function of the packet loss probability when using single or double transmission per packet. The results presented in Figure 3 show how the double transmission technique, presented in the access scheme, leads to a near-constant success probability even in the case of a high loss probability due to the message re-transmission (Albertengo G., 2013).

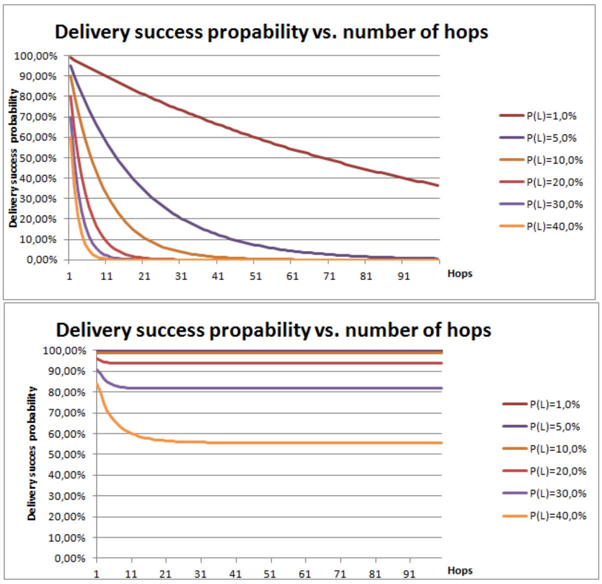

Figure 3 Delivery success probability – classic vs double transmission

The protocol design permits the automatic addition of new devices to the network through the entry of appropriate node address values in the gateway configuration files. A new node is automatically detected by the network, but being absent from a previous configuration, is considered as a mobile node and is ‘heard’ by the network, but is not formally part of it. Exploiting this network property, it is possible to detect the position of a mobile node (its position on the axis of installation of the WSN) starting from the computation of Radio Signal Strength Information (RSSI) values, which are collected by nodes of the network in communication range of the mobile node, called anchor nodes.

3.2 WSN-based system for indoor localization

Many indoor localization and positioning techniques have been proposed in the literature over recent years. Some proposed mechanisms, for example, those which deploy infrared cameras, ultrasonic or laser transducers, provide high accuracy but are very costly and suffer from several drawbacks, which make them less-suited to adverse and harsh environments that often result during an emergency situation (e.g. the presence of smoke and debris). Consequently, localization techniques which utilize RF measurements appear to be more promising candidates.

The literature reports numerous examples of localization methods based on signal strength of various RF frequencies (Lee K., 2011; Cotton S.L., 2011;Ladd A.M., 2004) As such, 2.4GHz was ultimately selected in this study as it is a widely used, low-power wireless technology designed for wireless mesh networks. Although an 802.15.4 proprietary protocol was used in implementing the indoor localization system, it is acknowledged that giving members of the public additional hardware solely for the purpose of location and tracking would be both intrusive and unfeasible. This paper presents a method of localization for travellers which would be compatible with the various wireless technologies built into a modern smart phone.

There are two main approaches in the localization problem that utilize radio features: those that estimate the distance between two wireless nodes and those that estimate the angle of radio reception. Angle of Arrival (AoA) techniques require complicated equipment (special antennas, antenna arrays, multiple receivers on one node), leading to remarkably high costs and complex deployment. For distance calculations, extremely high node synchronization demands make time difference techniques e.g. Time of Arrival (ToA) or Time Difference of Arrival (TDoA) unattractive, since the wireless nodes have limited processing capabilities. This therefore leaves the Received Signal Strength Indicator (RSSI) as the prime candidate for such range measurements.

In this work the proprietary 802.15.4 RF communications operate around the 2.4GHz frequency range and the RF signal strength is adversely affected by both the presence of water and the inclusion of metallic surfaces and objects. This can impede the effective distance these wireless devices can communicate with each other and also lead to erroneous readings.

3.2.1 System Design

The localization system comprises a number of Static Units, Mobile Units and a Gateway PC. The Static Units were fixed to the walls at a height of 2m and spaced approximately 10m apart within the infrastructure. Both the Mobile and Static Units share a common hardware design: a RF Solutions PIXIE module provides the range finding and microcontroller functions, this comprises a Texas Instruments CC2420 2.4GHz IEEE 802.15.4 transceiver with PCB antenna and a Microchip PIC18LF4620 8-bit microcontroller. The CC2420 was selected to handle the physical and MAC layers of the IEEE 802.15.4 proprietary protocol through the use of the RSSI estimate range. As SAVE ME was a proof of concept project, the production of technical data feeds on the power consumption of the localisation system was outside the scope of the project. Nevertheless, the localisation nodes were specifically designed to operate on a minimal power basis, reducing the need for hard-wiring into a mains power supply. They were contained within a simple yet robust casing (IP66 rated i.e. dust tight and protected against powerful jets of water which are used for periodically cleaning tunnel walls) for ease of maintenance and quick replacement. Both power requirement and maintenance factors were deemed particularly important for installation of reliable WSN systems in remote locations or at halfway points in long tunnels which were far from entry/exit points (Figure 4).

Figure 4 Localization node

3.2.2.Networking

This proprietary protocol (Brennan D., 2012) makes use of the smallest possible IEEE 802.15.4 packet size with the CC2420 appending the RSSI value to the end of any received packets. Carrier sense multiple access (CSMA) mode was enabled on the transmission from the CC2420 to avoid collisions on the shared radio channel. A linear feedback shift register (LFSR) was used as an efficient method of providing randomized timings between packet transmission attempts. The LFSR was seeded with the unique device ID to ensure that the pseudorandom sequence is different on each unit.

A Digi XBee ZB module provides the ZigBee on IEEE 802.15.4 physical and MAC layers which are used for the SAVE ME communications backbone for transmitting the range data back to the Gateway PC. For simplicity the two radio systems are physically separated and active on different channels within the 2.4GHz ISM band. A simplified schematic is shown in Figure 5.

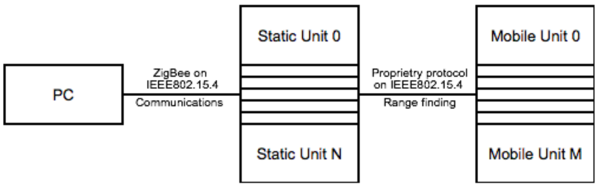

Figure 5 Simplified system diagram

The localization algorithm uses the RSSI values of a number of short broadcast packets from Mobile to Static Units and vice versa to calculate a relative ratio between a Mobile Unit and the nearby Static Units. The Gateway PC software receives the data from each of the Mobile and Static Units via the XBee ZigBee network. This incoming data is then queued up and periodically processed.

A map containing pairs of device IDs and averaged RSSI values is maintained and updated for each incoming data packet in the queue. Thereafter, for each Mobile Unit in the system all the pairs to Static Units with valid RSSI values are then processed to calculate a ratio for each Static Unit. These ratios are then applied to the positions of the Static Units and summed to form the determined position of the Mobile Unit.

3.3 VR-based visualization system

Developing acceptance of an emergency response platform relies heavily on both the correct training of operators and on the assessment of platform operation under simulated emergency conditions. The VR solution is formed from two integrated components: one responsible for simulation services, the other responsible for visualization. This separation of concerns, as employed throughout the SAVE ME architecture, provides inherent support for future extension, flexibility, and – ultimately – customer choice of components to be employed.

3.3.1.Simulation component

The simulation component employs discrete simulation techniques to derive optimal evacuation routes for vulnerable travellers within a facility. The simulation draws on aggregated data provided from, amongst other sources, the WSNs and contextualizes that against an environmental understanding drawn from a directed graph of the facility from which travellers must be evacuated. At the start of a simulation run, which may be repeatedly requested during any incident or training exercise, the simulation is aware of the location, number and individual abilities of travellers currently within the facility, the nature and location of the (real or simulated) incident, the structure of the facility, and the state of all possible evacuation routes through the facility itself.

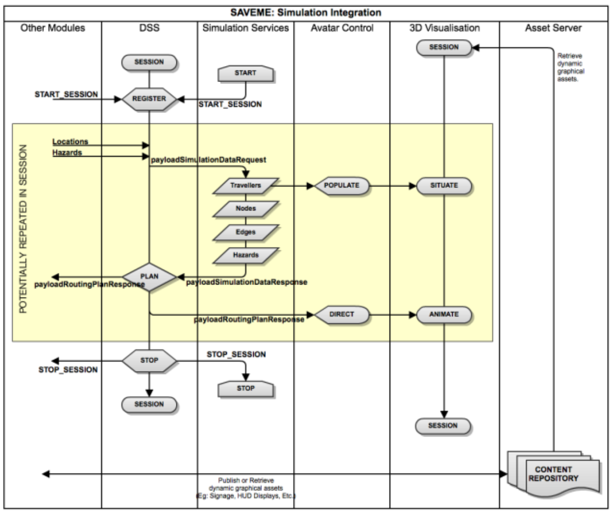

Figure 6 Simulation Integration in SAVE ME

Figure 6 illustrates the integration of the simulation component in SAVE ME. As can be clearly seen, the simulation components receives start state data from the data aggregation point (in SAVE ME, from the DSS but can originate from alternative aggregators if required) before calculating routing plan responses informed by unique traveller and event locations, the relative survivability of each major location in the facility, the predicted number of travellers moving through any part of the facility at any time during the evacuation, and the respective abilities of each traveller being planned for. An authoritative response, containing the set of routing plans and calculated node and edge weights for the graph of the facility, is then returned to the DSS or other upstream C2 system. During the course of each conversation between the simulation component and other aspects of the system, the custom communications schema is employed. The simulation component maintains no a priori knowledge of the facility in which it is deployed; relying instead on the provision of the facility graph from its upstream C2 system as part of the initiation process.
End-to-end execution times for the steps highlighted in Figure 6, including full logging to disk, averaged 300ms for a set of 50 distinct travellers in a facility graph containing 27 nodes and 38 edges. This execution speed meets the near real time requirement for decision support and permits multiple uses of the simulation component to plan and re-plan evacuation guidance as the incident progresses and the environment changes.
To achieve this performance, the simulation component made extensive use of multithreading capabilities: spawning distinct threads for each of its functional aspects. This allows, for example, the facility graph to be reconstituted in parallel with the creation of traveller and hazard maps; the results of each parallel thread then being provided as inputs to the simulation core for the purpose of calculating the state of each node within the facility and, thereafter, the optimal evacuation route for each vulnerable traveller group – driven by both ability and current location.

3.3.2.Visualization component

In contrast to the simulation component, which has no direct human interface and runs as a backend component, the visualisation component provides a high-touch, high-engagement HMI that allows for operational situational awareness and training activities alike. As seen in Figure 6, the visualisation component is directed by the simulation component and is, in operational terms, responsible for populating and directing a view of events as they happen within the real-world facility.
The visualisation component builds on the Open Simulator platform - an open-source clone of the SecondLife™ virtual world environment - to provide 1:1 scale 3D models of a facility. Models are produced, either entirely remotely or with a site visit, from a combination of architectural plans, photographs, and videos of the facility in question and typically take in the order of a few days to several weeks to construct (subject to the complexity of the facility, the amount of existing documentation, and the purpose to which the model is to be put). Once produced and validated, the resulting models may be used to support planning – including the production of the graph-based representation of the facility for use in systems such as SAVE ME; training – providing the opportunity for non-local or hybrid response teams to become familiar with both the facility and other team members, and operational activities alike. Users and operators interact with the 3D facility model through the use of a virtual world client through a desktop computer application available for all major operating systems. In the case of now available alternatives to Open Simulator, access to the virtual world may be through bespoke gaming client or directly in-browser where facility complexity permits.

Figure 7 Virtual Travellers Evacuate 'Monument Metro Station'

Figure 7 illustrates the use of the virtual world (Open Simulator) client with a model of the Monument Metro Station in Newcastle, UK (one of the SAVE ME pilot trial sites). The view presented is that of an operator or other user who is physically logged in to the system. The human avatars seen on the platform are programmatically generated and controlled by the simulation system as described in Figure 6. The different avatar styles indicate the set of vulnerable travellers being represented and each avatar is created at the near-exact locations of the real world travellers (as located within the accuracy limits of the WSN and localisation services in use) and move in accordance with their calculated specific, or the generic, evacuation plan.

Figure 8 Virtual Colle Capretto Tunnel

For the purposes of operational response, the visualisation component provides a clear and contextualised situational awareness regarding the facility at hand (Figure 8). The resulting situational awareness is described as contextual because, unlike the majority of situational awareness systems available at the time, the visualisation component delivers multi-dimensional information that is displayed according to a 3D representation of the facility at hand rather than to a flat (2D) map, floor plan, or image (eg: aerial, satellite, etc.). It is, therefore, possible to explore all connected data feeds in the direct context of the facility: including, where data feeds permit, external and environmental influences as well as direct sensor data from within the facility itself. The geosituation of that representation, at 1:1 scale, further assists with the development of understanding: both by tactical responders and by command and control personnel. While not explored during the SAVE ME project, such capability could also be provided to responders en route to the facility: saving valuable time in relation to understanding the situation to be addressed and the strategy through which to address it. Prior to operational conditions, however, the same visualisation component can be employed to assist with the development of operational response and evacuation plans and to provide an accurate training space for responders. This provides the opportunity to explore multiple tactics and techniques against a facility without requiring the closure of the facility or other impact to the day-to-day operations of that facility.

Whilst Open Simulator may be deemed beta code with poor documentation and some performance issues, and therefore is not expected to be the platform of choice for a production scale system, the ability to make use of a freely available platform with source code access was of interest and relevance to the team in relation to the SAVE ME project. Nearly four years after the start of the SAVE ME project, other – better – alternatives for the 3D representation of key transport hubs are now available. Regardless of the virtual world platform employed in any production system, the development process for 3D models is markedly similar to that described above.

In proving the utility of a VR platform for both training and operational situational awareness within SAVE ME, the practical utility of architecting such a solution in keeping with the principle of separation of concerns has been highlighted. While commercial customers may elect to use a different VR component in their own implementation (where, for example, a virtual world platform, gaming engine, or 3D GIS service is already deployed in that customer's operation), the optimised simulation component remains – with minimal extension - effective and able to instantiate, direct, and display relevant information within the VR component in use.

4 Demonstration

4.1 Application context: SAVE ME Pilots

The evaluation of the SAVE ME system was conducted under realistic conditions within two real-world facilities: the Colle Capretto road tunnel in San Gemini (Perugia, Italy) and the Monument metro station (Newcastle upon Tyne, United Kingdom) (SAVE ME, 2012).

4.1.1.Tunnel Pilot

While early pilot developments related to trial use-cases for SAVE ME were defined in collaboration with tunnel rescue operators at the Gotthard Strassentunnel (Swiss-Italian border), operational limitations meant the final trial site selected was the Colle Capretto tunnel in Italy. Figure 8 provides an illustration of the Perugia-side entrance to this tunnel, as represented in the VR system visualisation component.

Colle Capretto is 1,171m in length and is located near San Gemini in Italy, forming part of the SS3bis national road (which is part of the E45 TEN route). It is a dual-bore construction tunnel, with traffic running in a single direction through each bore. The tunnel is monitored from a control room located in Perugia (about 70km to the north), not at the tunnel site itself. The SAVE ME trial involved only one of the tunnel tubes; arranged to provide a two-way, single-bore environment as originally planned in conjunction with the Gotthard tunnel.

The SAVE ME trial took place on 31st May 2012. Both tunnel bores were closed for safety reasons whilst a multiple vehicle accident with dense smoke was simulated towards the centre of the tunnel. The traditional exits were blocked, and a "virtual" exit was defined which travellers and rescuers were supposed to reach with the additional support of SAVE ME system. The trial itself involved two experimental runs with 40 volunteer 'travellers' (including older adults and children), 15 fire-fighters, five ambulance personnel and five infrastructure operators.

Prior to the trial, a week of training was delivered to fire-fighters (from both the Perugia and Terni regions of Italy as well as Gotthard Strassentunnel personnel), policemen and tunnel infrastructure operators. This training session also provided team building opportunities which was evidenced by the observed co-operation between the various actors during the trial. During the training, organised by CNVVF at the "Istituto Superiore Antincendi" in Roma, all technologies were presented to the trainees and live sessions with the VR tools arranged.

The installation for Colle Capretto (in the North-South direction tube), involved the deployment of sensing, localization and communication devices positioned in a 300m long area encompassing the only safety exit within the tunnel itself. This location starts from 590m inside the north entrance and ends 890m from the north entrance (290m from the south entrance). Outside of the tunnel, a mobile command post vehicle was deployed as the ‘bronze’ command location for all external-to-facility components. A wired Ethernet network was used to connect all machines at the command post location, linked to the gateways to in-facility systems through a wireless point-to-point 5.4 GHz link inside the tunnel.

The WSN packages for the tunnel trial comprised the installation of 10 WSN (+1 mobile node) for environmental detection, signalling and rescuer localization and 30 fixed (+ 20 mobile nodes) for localization of the trapped travellers. All WSN packages were sufficient to envelop the trial zone within the tunnel with environmental, localisation and signalling services.

The VR package for the tunnel trial comprised a single small-form factor server containing a 1:1 scale model of the tunnel trial site for visualisation purposes and a low specification netbook computer running the simulation component. This set of functional servers was augmented by a laptop workstation used as a C2 client to obtain the contextualised situational awareness of the trial incident.

4.1.2.Metro Pilot

Monument Metro Station on the Tyne and Wear Metro light rail system forms a key transport interchange between the different metro lines of the system as well as with on-street bus services. Monument station also serves the main shopping and leisure districts of Newcastle City Centre as well as being close to St. James' Park, home of Newcastle United Football Club.

The Monument trials took place overnight from 20th - 21st June 2012, during which two individual scenarios were implemented, one simple and one complex. The key aim of the Newcastle pilot trials was to test the intelligence and adaptability of the DSS and consequential output messages to the various devices and displays.

The simple scenario involved a (simulated) fire starting in one of the litterbins on Platform 2. The position of the bin in question was strategically chosen so that it would force passengers in the immediate vicinity to evacuate via two separate routes to the different exits.

The complex scenario was designed to be slightly more involved to test the capability of the DSS to react to a chain of events. Here, a suspect package ‘leaking gas’ was placed in the same strategic location as the litter bin in the first scenario. Upon detection by the DSS, the evacuation strategy was started but then a second suspect package also ‘leaking gas’ was then detected by the main escalator. When this second package was detected, any passenger being directed towards that area would be rerouted by the DSS to exit via the staircase instead, taking a slightly longer and circuitous route.

The WSN packages for the metro pilot were of a similar number to that from the Colle Capretto trial, but this time instead of deploying a linear topology, a network topology was required to cover the entirety of platforms 3 and 4 within the overall station complex. Unlike Colle Capretto, the central DSS command post was set up within the station environment (in an area cordoned off specifically for the SAVE ME team) to allow the participants movements to be directly observed and also to mitigate the impact of the metallic panels on signal attenuation. All sensors were installed at a consistent height of 2m above platform level, using temporary Velcro fixings; in a real-world installation, it is envisaged that the sensors would be installed in positions that were out of view, but still within communication range, to minimise the visual impact on the station environment which is open to the general public, unlike in a road tunnel which has restricted access.

21 participants were recruited for the Monument trials covering both sexes, a range of age groups, nationalities and (assumed) familiarity with the layout of Monument Metro Station. Due to a concert taking place at the Stadium of Light in Sunderland the same evening, it was not possible to recruit any appropriate rescue personnel from the Metro Policing Unit as all their resource was required to oversee crowd control across various key points of the network.

4.2 Integration of Technologies

4.2.1.Data aggregation

The system developed and tested for SAVE ME involved a central Decision Support System (DSS). The DSS was responsible for both the determination and dissemination of personalized and mass evacuation strategies and provided the role of communications broker for all SAVE ME system components. While the DSS also provided data aggregation services in SAVE ME, fusing data derived from environmental and localization sensors against a graph schematic of the facilities into which SAVE ME was deployed, that role can be fulfilled by either available open-source, generic data aggregation systems, such as configurations of Mango, or by minimal extension of extant Command and Control (C2) systems. Achieving successful implementation of data aggregation services that may be used by both the WSN and VR systems described herein requires only the implementation of the custom SAVE ME communications schema or, if preferred, the implementation of an alternate communications schema, perhaps informed by the Common Alerting Protocol (CAP), within both modules.

4.2.1.WSN-VR cooperation within SAVE ME

The SAVE ME system defined an open, extensible, and flexible architecture into which numerous components could be integrated via a common communications schema**.** That schema, expressed in eXtensible Markup Language (XML), was produced from analysis of the static and dynamic behaviours required of SAVE ME components and provides a standardised method for information exchange.

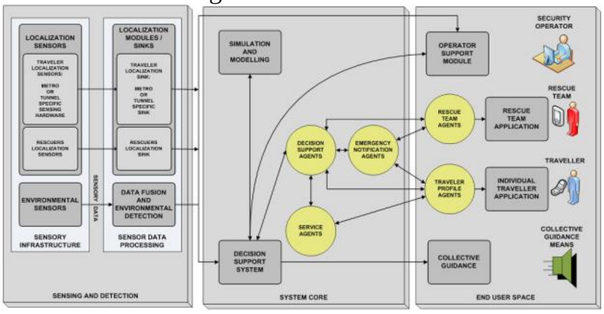

Figure 9 SAVE ME Architecture View

Figure 9 provides an architectural overview of the complete SAVE ME system as deployed during live trials. Divided into three domains, SAVE ME comprises Sensing and Detection services, in which the WSN resides; the System Core, containing the VR system components and the DSS, and the End User Space, within which practical use is made of operator and traveller facing components. The WSN and VR aspects communicate, as noted previously, through an intermediate broker. For SAVE ME, that role is played by the DSS but, again as noted, any broker may be employed in order to incorporate both WSN and VR capability into extant C2 infrastructures. The key enabler for such integration is the SAVE ME communications schema.

Data generated by the WSN propagates reliably and losslessly, via the broker component, to the VR system. The VR system then uses the received data to populate avatars and other relevant information within the 3D model of the facility in which the WSN is employed, bringing that model to life. It is relevant to consider this in a theatrical context: the VR system creates a 'stage' into which 'actors' and other aspects relevant to the 'script' are emplaced and animated in order to bring the story to life.

It should be noted that any real-world data that may be captured, either by extant sensors within the WSN or through augmentation of WSN nodes to include additional sensors or data from other subsystems, may be passed to both (a) the VR simulation component for purposes of information predictions or plans, and (b) the VR visualisation component as aids or additions to the provision of contextualised situational awareness.

For training purposes, recorded or stimulated WSN data may be passed to the VR system for use in the creation of scenarios against which response plans and responder performance may be developed and verified.

Regarding data payload sizes, it should be noted that the SAVE ME schema is an accretive schema that fits within and leverages the separation of concerns between components in order to minimise payload sizes wherever possible. In doing so, the data payload from WSN and localisation components to the central DSS or other C2 platform is considerably less, and requires considerably less overhead to construct, than the data payload between DSS and the simulation component. For reference, it should be noted that the largest payload size detected between the DSS and simulation components during the SAVE ME trials was 364KB. That size encompasses all location, environmental, and hazard data as well as providing the full graph representation of the facility and a Base-64 encoded image of the facility floorplan.

The accretive nature of the communications schema is a result of the expectation that the more central components (eg: the DSS, simulation, and visualisation components) will be co-resident on a wired network backbone (whether at a central office or within an incident response vehicle at the scene – as tested within SAVE ME trials at Colle Capretto). A side effect of this expectation is that multiple remote sites may be instrumented with WSN and localisation components which communicate over relatively low bandwidth bearers, including mobile data, to a common central office. In the case of mobile incident response vehicles, this also provides the opportunity for near real time data to be delivered to and exploited within the vehicle whilst it is on route to the incident itself. This would save further time in responders becoming aware of the situation at the incident scene and thus increase the amount of time available to focused on response, rescue, and remedy actions.

4.3 Evaluation and Results

Metrics have been defined in order to enable the measurement of the reliability and effectiveness of the components in the SAVE ME system, and assess the performance of the overall system in order to permit a robust evaluation. Indicators for the SAVE ME technical evaluation have been classified into three categories: Reliability, Application Performance and System Performance.

A series of laboratory-based testing of the various components in the SAVE ME have been deployed before real-world testing on a stand-alone basis, with iterative development to expand the functionality of the components to a stepwise procedure. Finally, full-scale pilot testing took place.

All technical metrics have been recorded using system log files.

4.3.1.Laboratory testing

During the SAVE ME project, 9 laboratory tests have been conducted. They were meant to test and evaluate the single modules of the system, in order to provide a solid basis for the final on-site tests. This section presents the pre-pilot evaluation of the WSN components, starting with the WSN-based system for road side applications.

As in any multi-hop WSN protocols, power consumption differs node by node, with the node nearest to the final destination having the worst power consumption since it has to forward the highest number of messages. In our system, with 50 nodes, at the maximum BEACON frequency, the duty cycle is 8.6%.

From the point of view of power consumption, since the radio interface consumption is some 20mA @ 3.3 V, the resulting average radio current consumption in the worst case 1.86 mA @ 3.3V = 6.16 mW. The power consumption depends from node to node, furthermore, the node that is closest to the GTW will spend more energy as it represents the point transited by all information and all commands.

The capacity of the network, at radio packet level, is up to 500kbit/s. The outdoor line-of-sight between nodes is up to 100m.

In order to evaluate network performances, a test sensor network with five nodes was active for 30 days, with a packet send period of 0.5 s. The resulting packet loss rate was between 4 and 10% (for an indoor scenario).

Localization tests were also conducted in an indoor environment, by deploying ten nodes, each 10m from the next, and performing RSSI measurements for neighbouring nodes every metre. Results show how the interpretation of RSSI slopes can provide localization information with an accuracy equal to half of the distance between the nodes. Figure 10 shows RSSI values for two nodes in a 30-measurement experiment: the measured accuracy is 5m.

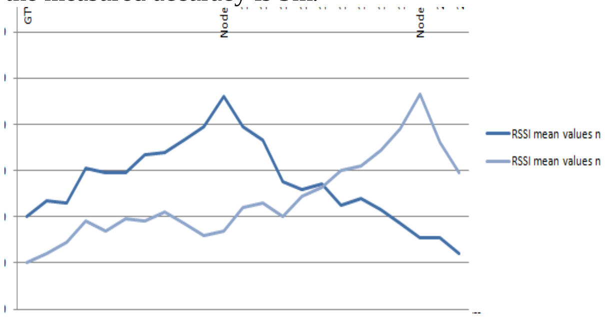

Figure 10 Lab measurements for indoor localization

In case of the WSN-based traveller localization system, shown in Figure 11 is the average RSSI of a mobile node at a given distance from a static node as reported by the system (The results are derived from an experiment involving one static and one mobile node). It can be seen that although the RSSI value fluctuates due to environmental factors there appears to be a linear tread up to 10m, allowing the system to calculate the distance from individual nodes with increased accuracy at lesser distances.

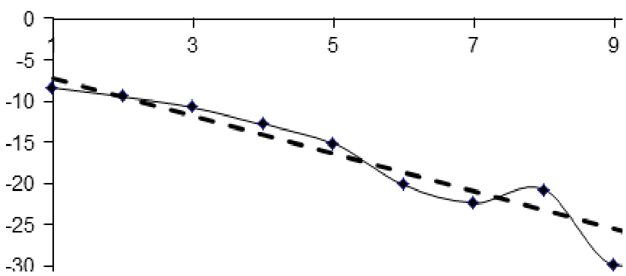

Figure 11 RSSI Signal Strength as a function of distance

In particular, two different topologies have been tested:

- a straight line (like in a tunnel)
- a square 2D topology (like in the metro station) with a distance of 7.5m between each localization module (around the perimeter)

In the first test, a node was moved to known locations on a straight line where localization modules were been installed and the detected position was measured.

In the second test 8 localization modules were set up, then a mobile node was placed at a known location and its detected position measured.

The experiment has been repeated four times for the first test, and five times for the second.

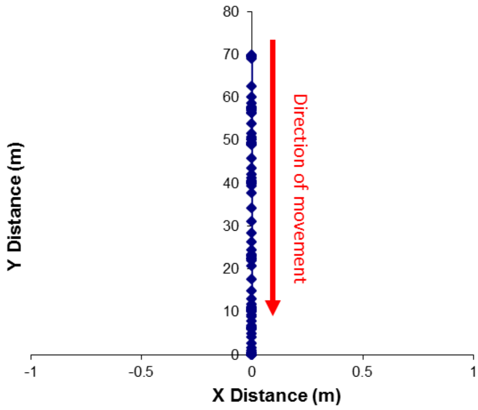

Figure 12 Localisation Accuracy – Linear Topology

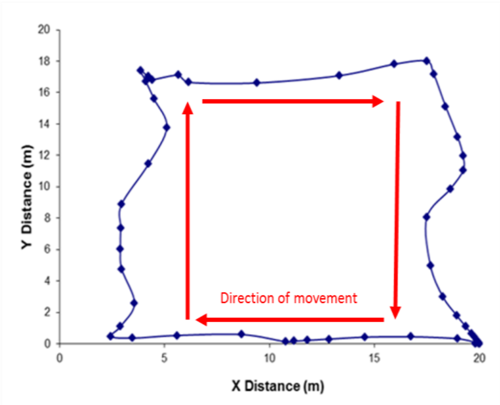

Figure 13 Localisation Accuracy – Network Topology

Figure 12 and Figure 13 represent respectively the detected position of the nodes in the different tests. From analysing the data, it was found that 100% of the nodes in the first test (tunnel-like environment) were detected within threshold (even considering the most stringent threshold of 3m) whilst 62% of the nodes in the second test (metro-like environment) were detected within this threshold.

4.3.2. On-field pilot testing

The performance of the SAVE ME application and system can be defined as the level at which it operates under emergency conditions.

Latency is a significant metric for the SAVE ME system as for any system involved with the safety and security of humans, the time taken to identify the event and implement the appropriate mitigation strategies is essential. The performance of the WSN network for road-side applications was evaluated by measuring the verified latency using the DSS logs to cross-reference the creation timestamp of messages sent by the WSN to the DSS with the logged reception time. The number of messages with a reception delay longer than 60 seconds were counted and used to assess the system latency. The number of messages with a latency value greater than 60 seconds was 8/229 (3.5%).

For the rescuer localization in the tunnel the mobile node was detected within a pre-specified threshold of 15m during the whole demo duration, by monitoring the actual position of the rescuer.

Accuracy is of crucial importance to SAVE ME, both in terms of the level of positioning of people within the transport infrastructure, and for the detection and verification of an emergency event. Regarding the accuracy of the traveller localisation system, the results from the trials and additional laboratory based testing indicated optimal performances in a linear topology (as per the Colle Capretto trials, Figure 12) but does not have quite the same level when dealing with a full network in a ring topology (which was more akin to the trials within Monument Metro Station, Figure 13). It was also found that the ring topology returned a better accuracy in the y-dimension than in the x-dimension; this finding requires additional investigation and testing to determine why this may have been the case. Though it was not possible measuring the exact position of the travellers during the actual trials, by examining the logs, it emerged that all (19) participants' IDs were correctly detected. Therefore, it can be stated that 100% of the proportion of public area floor space were monitored by the SAVEME system for the localization of travellers.

Results from evaluation based on user feedback showed that 95% of participants declared that the SAVE ME system could improve the general evacuation procedure of travellers in emergency situations; 60% believed a SAVE ME system would change the way they would behave if faced with an emergency situation

For the simulation and visualisation components, both trials were deemed to be successful activities that both confirmed expectations and highlighted areas for improvement. For both trials, the simulation component functioned exactly as expected and stimulated the visualisation component accordingly.

The final integrated system allowed both the preparation of an effective training set up and a smooth real-time presentation of the on-going scenario during the trials: the evolving situation as read by the sensors and the position of travellers and rescuers were realistically presented in the control room.

5 Conclusions and Future Work

From a technical perspective, the added value of the SAVE ME initiative was (i) development of a protocol and a data structure that contextualised a site by graph models, (ii) proof that the architectural principles of separation of concerns is exceptionally relevant in the context of complex, multi-component systems for real-world deployment, and (iii) provision of a mechanism through which real-time data could be exchanged in order to provide additional useful services for all involved actors. The technologies and general concept presented in this paper have been recognised by the rescue teams involved in the SAVE ME project trials as highly valuable for assisting preparedness and reaction to emergency situations. Therefore, solutions based on the SAVE ME approach may (i) improve the work of rescuers, (ii) reduce the overall evacuation time, and (iii) ultimately increase the level of safety of transport infrastructures.

The WSN technologies can be further exploited for monitoring the environmental conditions along the road/tunnel if coupled to a larger number of sensors on-board, for an early identification and localization of abnormal conditions, resulting in the adoption of appropriate preventative measures and ultimately the reduction of response times. The advanced level of industrialization of the WSN components may lead to a quick adoption by safety authorities. Nevertheless, further research is needed for the identification of proper standards and performance levels needed for the definition of operational procedures. Further testing is needed in order to establish the limits of the SAVE ME WSNs in terms of their scalability. This needs to be accompanied by regular technological updates and meetings between authorities and industries aimed at identifying ways of systematically integrating WSNs into current safety systems.

The adoption of VR tools in training and planning is highly desirable, in particular the 3D representation of the actual or simulated conditions at the incident site which may result in a dramatic improvement in understanding what travellers and rescuers are facing or could face in a real event. Temperature and visibility conditions are excellent examples of what will be possible to sense/measure and graphically represent in 3D fashion. Integration of localization capabilities has been signalled as another key aspect to help monitoring mass behaviour and supervision of on-field personnel, giving the possibility to make better decisions based on what is actually occurring in the affected environment or situation.

On final, important consideration is that any system is meant to be used in a critical environment, during an emergency, and therefore the power autonomy is considered a key element to be achieved by all components in any further development beyond the SAVE ME project.

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